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13. ABSTRACT (Maximum 200 words) This research program is aimed at the development of a soil-tire interaction model based on Contact Mechanics Theory. The model developed obviates the need for <i>a priori</i> knowledge of soil-tire contact properties and instead relies on directly and accurately measurable quantities. Other major research outcomes of this program include: 1) the first complete solution to the frictional contact problem between a granular material and a deformable solid, 2) extension of the Double Shearing theory for dilatant granular flow to three-dimensions and 3) the development of a new technique for the micro-mechanical analysis of granular media.					
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**A LARGE DEFORMATION FINITE ELEMENT ANALYSIS OF SOIL-TIRE
INTERACTION BASED ON THE CONTACT MECHANICS THEORY OF
ROLLING AND/OR SLIDING BODIES:**

FINAL REPORT

Antoinette Tordesillas

June, 2000

**US ARMY RESEARCH OFFICE
Grant Number DAAG55-97-1-0320**

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1. STATEMENT OF THE PROBLEMS STUDIED

This research program was aimed at the development of a three-dimensional computational model of the soil-tire interaction system. The program was divided into four stages of development. The problems considered in each stage are summarized below:

PERIOD 1 (Jun 1-Nov 30, 97)

The aim was to develop complete stress and displacement/velocity solutions for a granular soil subject to a series of frictional indenting bodies using the rigid-plastic *Double Shearing Theory for Dilatant Materials* as the soil model. The rigid indentors considered were: flat plate/punch, wedge, wheel, rolling rigid wheel.

PERIOD 2 (Dec 1,97-Nov 30, 98)

The aim was to develop a finite element model of a deformable cylinder in surface contact with a semi-infinite granular soil. The two cases of vertical indentation and rolling contact of an elastic cylinder were examined. An elastic-plastic double shearing theory was used to model the soil.

PERIOD 3 (Dec 1,98-Nov 30, 99)

The aim was to develop a working two-dimensional model of the soil-tire interaction system, and to begin extension of this model to three dimensions.

PERIOD 4 (Dec 1, 99-May 31, 00)

The aim was to continue the development of a three dimensional model of the soil-tire interaction system. However, upon reaching this stage we were confronted with two major problems in the mechanics of vehicle-terrain interaction: (i) lack of experimental data against which our models could be evaluated and (ii) ill-posedness of classical continuum models for the soil. In considering these issues, we thought it sensible to postpone further work on the three dimensional extension of our model and instead focus on resolving (ii) above by developing a micromechanics model for granular soil. This new line of investigation was performed under the guidance of Dr John Peters.

2. SUMMARY OF KEY RESULTS

2.1 Research Needs in 1995

The study of soil-tire interaction straddles many disciplines, most prominently the Mechanics of Soils and Granular Media, Mechanics of Soil-Tire Interaction, and Contact Mechanics. When I commenced my studies on soil-tire interaction (through my 1995 ARO-STIR grant) the state-of-knowledge and major research needs in these areas were:

A: Continuum Theory of Soils & Granular Media

- (1) Numerous models of granular soils exist. The "best model" is a highly controversial issue because not one of these models is capable of accounting for all major phenomena observed in practice.
- (2) Experiments have shown that important microstructural mechanisms (at the particle scale) govern the bulk behaviour granular media. Models developed within the framework of Classical Continuum Theory are therefore questionable, because the Continuum framework is based on the assumption that such microstructural effects are negligible. Moreover, these models are mathematically ill-posed (i.e. they have non unique solutions).

B: Mechanics of Soil-Tire Interaction

- (1) Existing models depend on the soil-tire contact properties (i.e. size & shape of the soil-tire contact area, and the stresses and displacements of each point within this area) **for input**. These properties, however, are extremely difficult if not impossible to measure. As such, **models are developed on *ad hoc* assumptions about the soil-tire contact properties which then severely limit their predictive capabilities.**
- (2) Models of soil-tire interaction require a reliable soil model. A moving tire causes the soil to undergo large deformation and flow which must be captured by this soil model. This added demand on the soil model further complicates A(1).
- (3) Experimental data to support and validate modelling activities are lacking.

C: Contact Mechanics

Contact Mechanics is that branch of Mechanics that has been specifically devoted to the analysis of problems germane to the modelling of interaction systems. It has a strong record of success in modelling interaction between solids, viz. steel and/or rubberlike bodies. A key feature of this modelling technique is that *input parameters to the model consist of directly measurable quantities* (e.g. global forces on the bodies and their undeformed geometries). The contact properties (which serve as input parameters in past models of soil-tire interaction as stated in B(1)) form part of the model's **output**.

- (1) Applications to **granular**-solid interaction systems have not been explored.

2.2 Accomplishments

Our research activities have addressed all of the above to varying degrees except for the experimental requirement B(3). Although the driving force behind our work was to better understand the soil-tire interaction system, our studies involved the use of tools and knowledge from the disciplines of Mechanics of Soil and Granular Media and of Contact Mechanics. These tools often needed modification or, in some cases, a major extension before they could be applied to the study of soil-tire interaction. Where we have made the necessary extension, our contribution to the advancement of knowledge therefore impacts on these disciplines as well. Below is a list of our accomplishments listed in the form:

YEAR; Project

Statement of accomplishment

Research need addressed as referred to in Section 2.1

1995 ARO STIR Project

- The feasibility of applying Contact Mechanics to soil-tire interaction is proven.

(B)(1)

1996 NSF- Research Stimulation Award

- Examined "best candidate models" for granular media for use in soil-tire interaction modelling.
- Developed *granular*-solid (rigid) interaction models incorporating *incompressible plastic flow* using the Double Shearing model for granular soils.

(A)(1) (B)(1) (E)(2) (3)(1)

1997 ARO Project 36555-GS - PERIOD 1

- Accounted for *dilatant plastic flow*: note that dilatant (volume expansion) plastic flow typically occurs when a granular material is subject to applied stress.

(B)(1) (3)(1)

1998 ARO Project 36555-GS - PERIOD 2

- Incorporated *interfacial friction*.

(B)(1) (3)(1)

1999 ARO Project 36555-GS - PERIOD 3

- Reformulated the Double Shearing model for granular soil within the framework of the Finite Element Method (FEM), and extended it to accommodate *three-dimensional deformations*. This is a necessary step in the transfer of technology to the end-user (since most engineering models and simulations are based on this computational procedure)
- Developed a *FEM granular*-solid (rigid) interaction model.
- Incorporated *deformability of solid* to FEM Model
- Developed an *FEM soil-tire interaction model*
- Model validation: only a partial validation could be performed due to lack of experimental data (as identified in **B(3)**).

(B)(1) (B)(2)

2000 ARO Project 36555-GS - PERIOD 4

- Opened up new pathways in the micro-mechanical modelling of granular media

(A)(2) (B)(2)

3. ARMY COLLABORATIONS & LINKS

Every step was taken to construct the soil-tire interaction model according to the US Army's needs and requirements. In doing so, the PI has established links with several US Army Laboratories, especially the Geotechnical Laboratory of the US Army Waterways Experiment Station.

- [1] US Army Waterways Experiment Station, Geotechnical Lab
 Date: *regular* contact
 Army Personnel: Dr John Peters and Dr David Horner
- a) My research group are currently collaborating with Dr John Peters and Dr David Horner to address one of the leading research needs in the area of off-road vehicle mobility: *Constitutive modelling of granular media*.
- b) The collaboration mentioned above has resulted in an Australian Academy of Science grant-in-aid for a scientific exchange between WES (Dr John Peters) and the University of Melbourne (Dr Antoinette Tordesillas) to promote our joint research. The following exchange visits are scheduled:
 Dr John Peters to visit the University of Melbourne: June 14 -June 28, 2000
 Dr Antoinette Tordesillas to visit WES: January 15-Feb 2, 2001
- [2] US Army Cold Regions Research Laboratory
 Date: September 14-17, 2000
 Army Personnel: Sally Shoop & George Blaisdell
 I interacted with both Ms Shoop and Mr Blaisdell at the 13th International Conference of the International Society for Terrain-Vehicle Systems (ISTVS) in Munich last September. I played a major part in this meeting as Chairman of *Session 4: Design, Development and Operational Planning Tools* and as a contributor to the Panel Discussion on *How to Face the 21st Century*.
- [3] US Army Waterways Experiment Station, Geotechnical Lab
 Date: September 14-17, 2000 (ISTVS Conf in Munich)
 Army Personnel: Dr Nikki Deliman & Randy Jones
 Both Dr Deliman & Mr Jones were at my ISTVS talk and we had numerous discussions throughout the meeting.
- [4] US Army Tacom-Tardec
 Date: September 14-17, 2000 (ISTVS Conf in Munich)
 Army Personnel: Dr Michael Leatherwood, Dr David Gunter & Dr Daniel Herrera
 They saw my talk at ISTVS, and approached me afterwards for a discussion.

4. PUBLICATIONS OVER GRANT PERIOD JUNE 1997-PRESENT

- [1] Tordesillas, A. and Shi, J. (1998) "Indentation of a double shearing granular material by a smooth rigid wedge", *Quarterly Journal of Mechanics and Applied Mathematics* 51 Pt 4, 633-646.
- [2] Tordesillas, A. and Shi, J. (1999) "Frictional indentation of dilatant granular materials", *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 455 No. 1981, 261-283.

- [3] Loudon, C, and Tordesillas, A. (1998) "The use of the dimensionless Womersley number to characterize the unsteady nature of internal flow", *Journal of Theoretical Biology* 191, 63-78.
- [4] Hill, J.M., Shi, J, Tordesillas, A. and Wu, Y.H. (1999) "The velocity field for the punch problem for dilatant granular materials" *Quarterly Journal of Mechanics and Applied Mathematics*, 52 Pt 1, 99-110.
- [5] Tordesillas, A. and Shi, J. (2000) "The rolling contact of a rigid circular cylinder on a semi-infinite granular material", Invited paper for the Honour issue of the *Journal of Engineering Mathematics* 37, 231-252.
- [6] Tordesillas, A. and Shi, J. (1999) "Finite element analysis of three-dimensional deformation and flow of dilatant granular materials— I. Theory", *Journal of the Mechanics and Physics of Solids* (submitted).
- [7] Tordesillas, A. and Shi, J. (1999) "Stresses, flow and deformation of soils in contact with metallic and/or rubber-like bodies" *Proceedings, 13th International Conference of the ISTVS* 1, 201-208.
- [8] Tordesillas A, Hughes BD and Zhang X (2000) "A micromechanical model of granular media incorporating particle rotation and its role in the evolution of anisotropy" (in preparation)

Other Publications

12 US Army Research Office Technical Reports

5. PROFESSIONAL AWARDS & GRANTS OVER GRANT PERIOD 1997-PRESENT

2000 The JH MICHELL MEDAL for distinguished research in Applied Mathematics awarded by the Australia and New Zealand Industrial and Applied Mathematics (ANZIAM) society.

2000-2001 Australian Academy of Science – Scientific Visits to the USA, Canada & Mexico "Constitutive Modelling of Granular Media". To perform research at the Geotechnical Laboratory, US Army Corps of Engineers Waterways Experiment Station USA

2000-2003 a small part on a US National Science Foundation CAREER Award to Dr Catherine Loudon University of Kansas "Air sampling characteristics of insect antennae". USA

2000 National Science Week "Real World Mathematics in Action? *I'd like to see that!*". The University of Melbourne, AUSTRALIA

6/1997- 5/2000 US Army Research Office -Single Investigator Award "A large deformation, finite element analysis of soil-tire interaction based on the contact mechanics theory of rolling and/or sliding bodies". The University of Melbourne, AUSTRALIA

2000 Department of Mathematics & Statistics, The University of Melbourne "The use of mathematical modelling combined with virtual reality experiments to develop micromechanical constitutive models of granular media"

1999 Australian Research Council Small Grant "Incorporating density effects on the modelling of flow and deformation of granular materials". The University of Melbourne, AUSTRALIA

1998 Australian Research Council Small Grant "A mathematical model for surface corrugation on unsealed roads" (jointly held with Professor JM Hill, Centre for Engineering & Industrial Mathematics, The University of Wollongong, AUSTRALIA)

1997 Australian Research Council Small Grant "Effective properties of granular materials and colloidal aggregates". This grant is jointly held with Professor BD Hughes (Univ Melbourne)

CONFERENCES & INVITED LECTURES OVER GRANT PERIOD 1997-PRESENT

Feb 2000 36th Australia and New Zealand Industrial and Applied Mathematics Conference "Micromechanical Constitutive Modelling of Granular Media" by A Tordesillas (NEW ZEALAND)

1999 13th International Conference of the ISTVS "Stresses, flow and deformation of soils in contact with metallic and/or rubber-like bodies" by A Tordesillas (GERMANY)

- a) Peer reviewed paper for oral presentation: "Stresses, flow and deformation of soils in contact with metallic and/or rubber-like bodies"
- b) Invited to Contribute to the Panel Discussion: "How to Face the 21st Century"
- c) **Chair** - Session on **Design, Development & Operational Tools**, one of the four main sessions in ISTVS

1999 Interfacial Continuum Mechanics "The Continuum Mechanics of Granular Materials: Are we back to square 1?" by A Tordesillas (AUSTRALIA)

1999 3rd North American Workshop on Modelling the Mechanics of Off-Road Mobility. "The modelling of dynamic contact systems involving granular soils" by A Tordesillas (USA)

1999 (Invited Lecture) Department of Mathematics, Purdue University. "The contact mechanics and kinematics of granular materials" by A Tordesillas (USA)

1999 Australia and New Zealand Industrial and Applied Mathematics Conference "Stranger than friction: micromechanics of granular flow" by A Tordesillas (AUSTRALIA)

1998 Australia and New Zealand Industrial and Applied Mathematics Conference "Frictional indentation of dilatant granular materials" by A Tordesillas (AUSTRALIA)

1998 International Symposium on the Mechanics of Plants, Animals and Their Environments: Integrative Perspectives "The use of the dimensionless Womersley number to characterize the unsteady nature of internal flow" by C Loudon (presenter) and A Tordesillas (USA)

1998 34th Australia and New Zealand Industrial and Applied Mathematics Conference "Frictional Indentation of Dilatant Granular Media" (AUSTRALIA)

1996 2nd North American Workshop on Modelling the Mechanics of Off-Road Mobility. "A contact mechanics approach to the soil-tire interaction problem" (USA)

1996 International Symposium on Olfaction and Taste XII and AChemS XIX "Characterization of unsteady flow at a chemosensory surface by the dimensionless Womersley number" by C Loudon (presenter) and A Tordesillas (USA)

1996 Annual Meeting of the Society for Integrative and Comparative Biology "The use of the dimensionless Womersley number to characterize the unsteady nature of flow" by C Loudon (presenter) and A Tordesillas (USA)

6. PROFESSIONAL APPOINTMENTS

- [1] **Associate Editor**, Journal of the Australian Mathematical Society: Series B-Applied Mathematics
- [2] Appointed to the **Executive Board, Australia and New Zealand Industrial and Applied Mathematics (ANZIAM) Society**

7. STUDENT RESEARCH TRAINING OVER GRANT PERIOD 1997-PRESENT

- [1] PhD supervisor on project entitled: *Micromechanical Constitutive Modelling of Granular Media*. 1999
- [2] Supervisor for 620-391 Mathematics and Statistics-Topic A- Project title: *Modelling approaches to the deformation and flow of granular materials within the framework of local continuum theory*. 1999
- [3] Supervisor for 620-392 Mathematics and Statistics-Topic B- Project title: *Stress propagation through a frictionless granular media*. 1999
- [4] Supervisor for 620-391 Mathematics and Statistics-Topic A- Project title: *Indentation of a granular media*. 1998
- [5] Supervisor for 620-392 Mathematics and Statistics-Topic B- Project title: *The behaviour of granular material under rolling contact from a solid cylinder*. 1998

8. PARTICIPATING PERSONNEL

Dr Jingyu Shi (July 1997-May 1999)

Dr Xi Zhang (Nov 1999-June 2000)